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Analysis and Prediction of Dual-Mode Chemical and Electric Ionic Liquid Propulsion Performance

Brian R. Donius* and Joshua L. Rovey†
Missouri University of Science and Technology, Rolla, Missouri, 65401
(formerly University of Missouri-Rolla)

An analytical and numerical investigation of the performance of a dual-mode propulsion system using ionic liquids is presented. Chemical bi-propellant performance of select propellants is determined using Chemical Equilibrium with Applications. Comparison of predicted specific impulse of ionic liquids with hydrazine and UDMH show that the ionic liquid propellants have 3-12% lower specific impulse when paired with nitrogen tetroxide. However, when paired with hydroxlammonium nitrate, the specific impulse is comparable. Density Impulse for ionic liquids is found to be superior due to their higher density. Analytical investigation of an electrospray electric propulsion system shows that some ionic liquids are capable of operating in a purely ionic regime, providing very high specific impulse (~ 6000 sec). The predicted chemical and electric performance data will be used to quantify mass savings for representative dual-mode propulsion missions.

Nomenclature

CEA	=	Chemical Equilibrium with Applications
CPIA	=	Chemical Propulsion Information Agency
ε	=	Nozzle expansion ratio
e	=	Fundamental charge
g_0	=	Gravitational constant
HAN	=	Hydroxlammonium Nitrate
ILs	=	Ionic liquids
IRFNA	=	Inhibited Red Fuming Nitric Acid
ISP	=	Specific Impulse
K	=	Ratio of specific heats
$\dot{M}_i$	=	Mass flow rate of ion i
MW	=	Molecular weight
NTO	=	Nitrogen Tertroxide
P_2/P_1	=	Ratio of nozzle exit pressure to combustion chamber pressure
P_c	=	Combustion Chamber Pressure
q/m	=	Charge to mass ratio
R'	=	Universal gas constant
Tm	=	Melting temperature
UDMH	=	Unsymmetrical Dimethylhydrazine
V	=	Voltage
V_e	=	Exit velocity
WFNA	=	White Fuming Nitric Acid

* Graduate Research Assistant, Aerospace Plasma Laboratory, Mechanical & Aerospace Engineering, 210 Toomey Hall, 400 W. 13th St., Student Member AIAA.
† Assistant Professor of Aerospace Engineering, Mechanical & Aerospace Engineering, 292D Toomey Hall, 400 W. 13th St., Senior Member AIAA.

I. Introduction

COMBINATION of high-thrust chemical and high-specific impulse electric propulsion into a single dual-mode system has the potential to greatly enhance spacecraft mission capability. Ideally, the combined system would share both hardware and propellant to provide the greatest reduction in system mass and maximum spacecraft flexibility. In the following sections we describe and review the current state-of-the-art in dual-mode propulsion and ionic liquids. We then quantify the anticipated chemical and electric thruster performance of popular ionic liquids. Finally, we summarize predicted propulsion performance and identify orbit maneuvers of interest that will be used in future work to quantify the benefits of a dual-mode system.

A. Ionic Liquids

An ionic liquid (IL) is either an organic or non-organic salt in a molten (liquid) state. Because of its molten state, the cation and anion of the salt dissociate, but the overall liquid remains quasi-neutral. All salts will obtain this state if heated to the proper temperature, but there is a sub-group known as room temperature ionic liquids that can remain liquid at or below 293 K. Although known since 1914, recent developments in chemistry have allowed the number of known ILs to reach well into the hundreds.[1] The exact mechanism for this molten salt behavior has yet to be identified, making the prediction of IL properties difficult. However, in general, common properties of ILs are high conductivity, viscosity, and negligible vapor pressure.

Ionic liquids are being considered as replacements for traditional explosives and rocket propellants[2,3] and volatile industrial solvents in chemical processing. Although thought of as universally benign by most professionals, a joint publication recently sought to highlight the combustibility of many ILs as they approach decomposition temperature.[4] This work also pointed out that combustion of several ILs becomes drastically more vigorous when sprayed rather than combusted as a pooled sample. Other articles have suggested that IL hydroxlammonium nitrate (HAN) may be used as a substitute for hydrazine as a monopropellant.[5-7] These analyses show that HAN performance both in pure and mixed forms is on the same order as hydrazine. Lastly, hypergolic behavior for several ILs has been reported when combined with traditional space storable oxidizers.[8-10]

Ionic liquids have also been investigated as electrospray propellants.[11-13] Ionic liquids for electrospray application were initially investigated because of their low vapor pressure. Previous electrospray liquids had relatively high vapor pressure and would boil off the emitter. This interest evolved to include multiple studies that explored plume emission of electrospray ionic liquids. Results showed that a spray of an ionic liquid can approach a purely ionic regime (PIR) of emission similar to that found in field emission electric propulsion.

B. Dual-Mode Propulsion

The main goal of a dual-mode propulsion system is to reduce spacecraft mass and enhance flexibility through the use of common system resources. Examples of common resources are either hardware or propellant. The modes of propulsion can be characterized as the tasks to be performed by the propulsion system during a given mission. These include but are not limited to high thrust orbit transfer maneuvers, low thrust station keeping, low thrust orbital transitions, and precision low thrust pulses for attitude control. Although the dual-mode concept has been passed around the academic community for quite some time, focused research has been nearly nonexistent.

One of the few instances where dual-mode propulsion has been applied was the Mars Global Surveyor.[14] However, this system consisted of two chemical systems, a bi- and mono-propellant thruster. The system was developed on a tight budget and a rushed schedule dictated by the loss of the Mars Observer craft. The system consisted of a common fuel bi-propellant thruster and catalyst monopropellant thruster (Fig. 1). The bi-propellant thruster was used in conjunction with aero-braking to bring the probe into orbit around Mars; while the monopropellant system was used for attitude control. The common propellant to both thrusters was hydrazine.[14] This common propellant allowed for the integration of three identical tanks that were readily available, reducing costs. Dual-mode propulsion was selected for this mission not based on improved performance, but out of the desire to speed up development, cut costs, and ease integration issues due to the smaller size of the Delta II launch vehicle selected for the mission. Although the MGS does represent a dual-mode system its use of hypergolic propellants and catalyst

monopropellant thrusters leaves little room for improved performance, it is therefore necessary to examine new concepts for dual-mode propulsion.

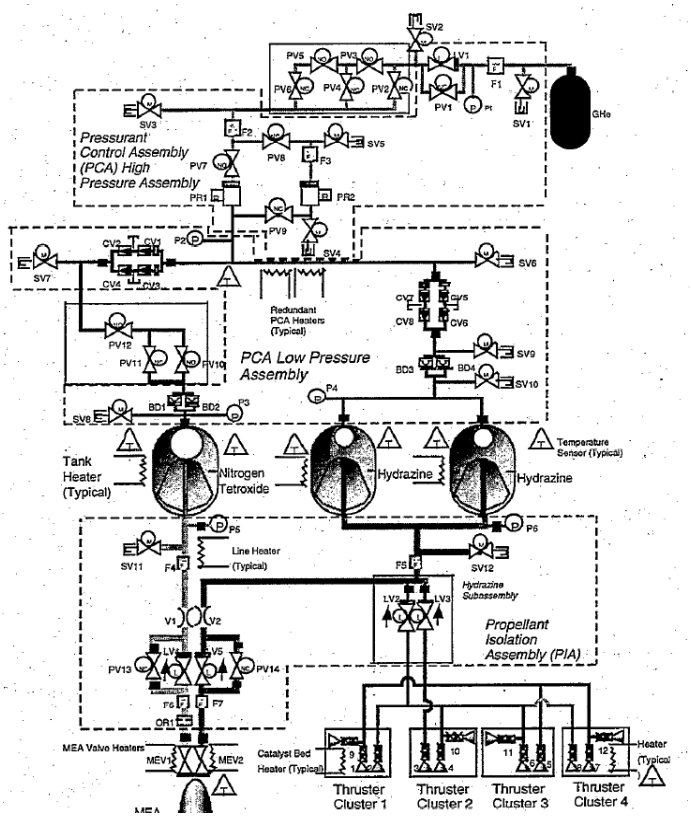

Figure 1. Mars Global Surveyor schematic showing dual-mode bi- and mono-propellant hydrazine thrusters[14]

II. Chemical Propulsion Analysis

The NASA Glenn Research Center, Gordon-McBride Chemical Equilibrium with Applications code is used to analyze chemical combustion and rocket performance of multiple bi-propellant combinations.[15] Specifically, ionic liquid fuels and oxidizers are paired with conventional fuel and oxidizer to determine rocket performance.

A. Investigated Fuels

Ten different ionic liquids were selected based on available literature data. To evaluate the capabilities of an ionic liquid fuel in a chemical propulsion system, it was first necessary to determine fundamental properties, such as heat of formation, melting point, and density. Because investigation of combustion properties of ionic liquids has only recently begun to receive attention, limited knowledge regarding heat of formation of these liquids has been determined. This led to the selection of 1-Butyl-3-methylimidazolium Dicyanamide and 1-Butyl-3-methylpyrrolidinium Dicyanamide as two of the IL fuels. Additionally, 1-Butyl-3-methylimidazolium Dicyanamide has been reported to have hypergolic reactions with standard storable oxidizers.[10] The heat of formation of both Dicyanamide IL's was determined through calorimeter tests and calculations using the quantum chemistry program Gaussian 3.[16-17] Reported results include a difference of approximately 1% between the calculation and experimental data. Heats of formation for eight energetic ILs based on 5-aminotetrazolate have also been determined.[18] To allow for a comparison with current space storable propellants, hydrazine and UDMH were also evaluated. Hydrazine has the greatest performance of all traditional storable fuels, but is highly toxic and notoriously unstable. UDMH has only slightly reduced performance from hydrazine, but a larger storable temperature range and greater stability. All thermodynamic data for these propellants can be found in Table 1.

Table 1. Thermo-chemical data for fuel and oxidizers investigated in this study

Fuel #	Fuels Name	Formula	H_f(KJ/mol)	Density (g/cm^3)	Melting Point (K)
-	Hydrazine	N_2H_4	-	1.01	274.69
-	UDMH	$C_2H_8N_2$	-	0.79	216
1	1-Butyl-3-methylimidazolium Dicyanamide	$C_{10}H_{15}N_5$	363.40	1.06	267
2	1-Butyl-3-methylpyrrolidinium Dicyanamide	$C_{11}H_{20}N_4$	218.90	1.02	223
3	Hydrazinium 5-aminotetrazolate	CH_7N_7	383.60	1.48	398
4	Guanidinium 5-aminotetrazolate	$C_2H_8N_8$	205.40	1.54	399
5	Aminoguanidinium 5-aminotetrazolate	$C_2H_9N_9$	302.30	1.51	366
6	Guanylguanidinium 5-aminotetrazolate	$C_3H_{10}N_{10}$	306.90	1.41	414
7	4-Amino-1H-1,2,4-triazolium 5-aminotetrazolate	$C_3H_7N_9$	565.00	1.62	387
8	4-Amino-1-methyl-1,2,4-triazolium 5-aminotetrazolate	$C_4H_9N_9$	546.00	1.46	249
9	4-Amino-1-ethyl-1,2,4-triazolium 5-aminotetrazolate	$C_5H_{11}N_9$	523.40	1.39	235
10	1,5-Diamino-4-methyl-1,2,3,4-tetrazolium 5-aminotetrazolate	$C_3H_9N_{11}$	655.10	1.57	444
	Oxidizers				
	Nitrogen Tertroxide (NTO)	N_2O_4	-	1.44	261.95
	White Fuming Nitric Acid (WFNA)	HNO_3	-	1.33	231.6
	Inhibited Red Fuming Nitric Acid (IRFNA)	83% HNO_3 +14% N_2O_4 + 2.4% H_2O + .6% HF	-	1.59	216
	Hydroxlammonium nitrate (HAN)	NH_3OHNO_3	-79.68	1.83	316.05

B. Investigated Oxidizers

Four oxidizers were selected for the combustion analysis. One of the oxidizers, hydroxylammonium nitrate (HAN), is an ionic liquid. The other three are common to current state-of-the-art chemical rocket systems. Specifically, nitrogen tertroxide (NTO), white fuming nitric acid (WFNA), and inhibited red fuming nitric acid (IRFNA) are considered. NTO is a highly toxic, storable, space oxidizer with extensive flight heritage and in most reactions provides the best performance. WFNA is essentially pure nitric acid doped with a small percentage of hydrofluoric acid to permit storage in a variety of container materials. In general, WFNA has reduced performance compared to NTO, but, aside from being corrosive, it is relatively benign. In terms of percentage by mass, IRFNA is 83% HNO_3, 14% N_2O_4, 2.4% H_2O, and 0.6% HF. In general, IRFNA usually has the same performance as WFNA, but has a far reduced melting point. The ionic liquid HAN was selected because of afore mentioned interest in HAN-based monopropellant systems. For the combustion analysis, HAN is considered as an oxidizer in a pure liquid state at 316.05 K.

C. Performance Criteria and Simulations

In this project the measures of performance selected for investigation are specific impulse (ISP), density impulse, and storability. Specific impulse is defined as the thrust per unit weight flow rate of propellant and represents how efficiently a system uses propellant. It is determined from Eq. (1)[19] for ideal flows. The pressure ratio is determined by solving the transcendental equation Eq. (2) by assuming an area ratio (ε). Density impulse takes into account how easily the oxidizer-fuel combination can be stored. The storability of the propellant for this project is qualitatively described as the need for additional heating or cooling of the propellant to maintain liquid phase in the storage tanks. This is important to reducing strain on the power system of the satellite and to prevent excessive propellant loss due to boil off. The storability for this study was quantitatively defined as the ratio of the melting point temperature of hydrazine to the melting point temperature of the ionic liquid Eq. (3). With this description, a value greater than one signifies that a propellant is at least as storable as hydrazine, while a value less than one signifies that additional heating of the propellant is likely to be required. To determine these measures of performance the chemical composition and thermodynamic state of the exhaust stream from the rocket combustion chamber must be known.

$$Isp = \frac{\sqrt{\frac{2K}{K-1}\frac{R'T_0}{MW}\left[1-\frac{P_2}{P_1}^{\frac{K-1}{K}}\right]}}{g_0} \quad (1)$$

$$\frac{1}{\varepsilon} = \left(\frac{K+1}{2}\right)^{\frac{1}{K-1}}\left(\frac{P_2}{P_1}\right)^{\frac{1}{K}}\sqrt{\frac{K+1}{K-1}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]} \quad (2)$$

$$\text{Storablilty} = \left(\frac{T_{m,N_2H_4}}{T_{m,IL}}\right) \quad (3)$$

The NASA Chemical Equilibrium with Applications code was used to determine the performance of each propellant combination. This program has been under continual development since the late 1950's and offers users the capability to determine equilibrium composition and adiabatic flame temperature for any reaction.[15] A recent addition to the program also allows the user to define a new fuel given the heat of formation and molecular composition. A series of 1536 simulations were performed using CEA by varying P_c, equivalence ratio, and propellant combinations for a fixed expansion ratio (ε) of 40.

D. Results

The chamber pressure was varied between 150 psia and 600 psia because these are typical levels in on-orbit engines.[20] As can be seen in Fig. 2, the variation of engine performance with pressure is minimal. This is to be expected because these relatively small pressures are not capable of greatly effecting the product species dissociation. Therefore all subsequent analyses will be restricted to the 300 psia case.

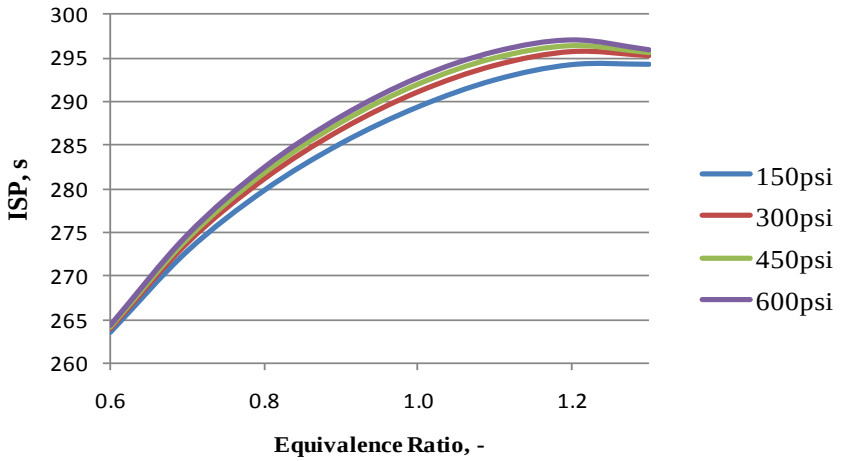

Figure 2.Variation of ISP with change in pressure for a sample ionic liquid

For the 48 propellant combinations, the mixture ratio was varied between 0.6 and 1.3 in order to find peak performance for each combination. An equivalence ratio of unity (stoichiometric) represents the point of complete combustion. Generally it was found that peak performance rested far to the right of the stoichiometric condition. This is a common result for rocket performance because as excess fuel is introduced to the system, molecular weight decreases faster than chamber temperature. A summary of the results for all oxidizer fuel combinations can be seen in Table 2a and Table 2b. All performance shown in Tables 2a and 2b is scaled with respect to the peak performance of hydrazine when combined with NTO (333, s and 406, g-s/cm^3). For example, UDMH-NTO has an ISP that is 97% of that obtained with hydrazine-NTO.

Table 2a. Summary of chemical propulsion – NTO and HAN oxidizer

	NTO		HAN		
Fuel	**Specific Impulse (-)**	**Density Impulse (-)**	**Specific Impulse (-)**	**Density Impulse (-)**	**Storability (-)**
Hydrazine	1.00	1.00	1.03	1.14	1.00
UDMH	0.97	0.85	1.01	0.97	1.27
1	0.88	0.91	0.99	1.13	1.03
2	0.94	0.95	0.99	1.11	1.23
3	0.96	1.16	1.00	1.36	0.69
4	0.90	1.10	0.96	1.35	0.69
5	0.92	1.11	0.97	1.34	0.75
6	0.91	1.07	0.97	1.29	0.66
7	0.93	1.16	0.98	1.40	0.71
8	0.93	1.12	0.98	1.33	1.10
9	0.93	1.09	0.98	1.31	1.17
10	0.94	1.16	0.98	1.38	0.62

Table 2b. Summary of chemical propulsion – IRFNA and WFNA oxidizer

	IRFNA		WFNA	
Fuel	**Specific Impulse (-)**	**Density Impulse (-)**	**Specific Impulse (-)**	**Density Impulse (-)**
Hydrazine	1.00	1.00	0.96	0.92
UDMH	0.93	0.85	0.93	0.79
1	0.90	0.96	0.90	0.88
2	0.90	0.95	0.90	0.87
3	0.93	1.18	0.93	1.07
4	0.88	1.13	0.88	1.00
5	0.89	1.14	0.89	1.02
6	0.88	1.09	0.88	0.98
7	0.90	1.20	0.90	1.08
8	0.90	1.14	0.90	1.03
9	0.90	1.11	0.90	1.01
10	0.91	1.19	0.91	1.07

Results show that hydrazine and UDMH provide higher ISP than each investigated ionic liquid fuel, regardless of the oxidizer. However, simulations also show that hydrazine and UDHM combustion with HAN oxidizer provides higher ISP than when combusted with NTO. With NTO oxidizer, the ionic liquid fuels have 3-12% lower ISP compared to hydrazine and UDMH. NTO out performed IRFNA and WFNA for any given propellant with the singular exception of 1-Butyl-3-methylimidazolium Dicyanamide, which resulted in only a small gain of five seconds ISP. IRFNA and WFNA have almost identical performance for any given propellant combination. When combined with HAN for ideal combustion, the performance of all fuels improved. That being said no IL-HAN combination resulted in superior performance to baseline hydrazine-NTO. However, the prediction of superior performance of HAN to NTO warrants further investigation.

In the area of density impulse the ionic liquids show superior performance to the traditional propellants, especially when combined with IRFNA and HAN. This is due to the greater density of the ionic liquids in comparison to that of hydrazine or UDMH. Density impulse takes into account how easily the oxidizer-fuel combination can be stored. This would seem to offer these propellant combinations a niche of small volume budgeted systems with proportionally high mass budgets.

Analysis indicates that storability of ionic liquids is a major difficulty. Only four propellants showed equal or superior storability than hydrazine (highlighted in green). As a result the remaining six propellants do not represent storable space propellants and are dropped from consideration in the remainder of the

study. With a storability factor of 0.87, HAN does not represent a storable propellant, but as it is substantially closer to hydrazine than any other ionic liquid that failed the criteria it will be carried forward in the analysis.

E. Error Analysis

Although CEA has been held in high regard for its predictive capabilities, it is still necessary to assess the accuracy of the performance predictions. To quantify the error in performance predicted by the code, a series of test cases were used to compare the CEA output with actual engine performance for systems found in the Chemical Propulsion Information Agency (CPIA) engine manual.[20] Given the mixture ratio, expansion ratio, and chamber pressure, the predicted ISP for equilibrium flow was compared to the actual performance (Fig. 3). Results show that as thrust level increases, the accuracy of the simulation increases. For engines with thrust levels less than 100 lbf, the values predicted by CEA for ISP were found to be on average 15.6% higher than that of test data, with a standard deviation of 3.7%. To ensure a more conservative estimate of ISP for a real system in future studies, a value of ISP 19.3% below the predicted values will be used representing a one standard deviation factor of safety.

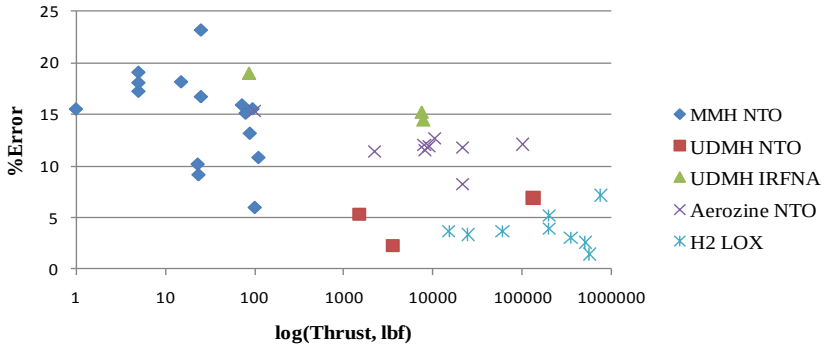

Figure 3. CEA error in ISP based on engine performance data from CPIA engine manual as a function thrust

III. Electrical Performance

A dual-mode propulsion system with common propellant must have an electric propulsion system that can operate with a combustible fuel. In this investigation, the focus is on ionic liquids. Electrospray electric propulsion systems have been operated with ionic liquids and are the focus of the electric performance analysis. Specifically, we use test results of ionic liquids similar to those proposed in this investigation to predict electric propulsion performance of an electrospray thruster operating with a combustible ionic liquid propellant.

A. Methods of Modeling Electrospray Propulsion

The traditional electrospray consists of emission of fine droplets from a micro jet that forms at the apex of an electro-fluidic structure known as a Taylor cone.[21] This cone is formed from the application of a start-up potential between a capillary containing a conducting fluid and an extractor grid downstream. Once formed, the applied voltage on the Taylor can be varied quite substantially, even to values below the start-up potential. Excessive voltages can result in the deformation of the cone and can even result in multiple secondary emission points. A stable Taylor cone emits droplets and ions in proportions dependent on the flow rate of propellant. Higher flow rates result in predominantly droplet emission, while minimum flow rate yields a nearly pure ion regime for some ionic liquids.

To quantify the performance of an electrospray propulsion system, initially two models for traditional solution based sprays were investigated.[21-22] Both models are empirically based on a series of dope polar solvent solutions. These models take a series of electrochemical properties and a proportionality curve between emitted current and dielectric constant to predict the specific impulse, thrust, and droplet size. Unfortunately, these two models are not valid for use with ionic liquids for various reasons. First there is disagreement between the two methods as to the functional form of the emitted current and dielectric

constant. Further analysis by Chen[23] suggests that the results of this curve may depend greatly on mobility of ions present in the fluid. Since ionic liquids typically are composed of complex ions it can be expected that ion mobility's for ILs will be very different from the conventional additives of polar solvent solutions. Second, the typical values of ionic liquid dielectric constant fall at the very edge of the range investigated in both models. Lastly, neither model is capable of predicting results near the pure ionic regime, which is of most interest to this study.

Although no formal method exists for modeling whether an ionic liquid can produce a pure ionic regime, emission close to PIR has been reported for several ionic liquids.[13,24] It appears that a general requirement is that the fluid possess high conductivity and surface tension and a relatively low viscosity.[25] For all but the most viscous fluids, a regime close to PIR has been induced by heating the fluid.[18] The properties of Fuel 1 (1.139 S/m and 0.0466 N/m respectively)[26,27] show that it falls into the reported range of conductivity and surface tension of the other fluids reported to have obtained PIR. Unfortunately, electrochemical data for HAN and Fuels 2, 8, and 9 are unavailable in the published literature. Therefore the two 5-aminotetrazolate based ILs were neglected outright. While it can be noted that if Fuel 2 could undergo PIR electrospray its performance would be virtually identical to that of Fuel 1 because of their similar molecular composition. HAN was maintained because it represents a known ionic liquid monopropellant and any resultant dual-mode system would be of high interest. Because fuel 1 has properties similar to those ILs that have shown PIR, [13,24,26,27] we assume it will operate in PIR with similar flowrates.

Emission in the PIR consists of pure ions and ions traveling with clusters of N number of neutral pairs (degree of solvation). A value from literature is then needed to approximate this value for the percentage of the mass flow that is pure ions and is ions of different degrees of solvation. This percentage can be determined from time of flight curves for IL's that have operated in PIR. This time of flight curve is produced experimentally by cutting flow rate to the emitter and measuring the current emitted as a function of time. The ions will arrive at the collector in order of least to greatest mass (higher solvation). Assuming an ideal collapse of emission a typical curve would resemble Fig. 4. The successive step down in current represents the final arrival time of a particular species and assuming that all emission strikes the collector would also represent the steady current contribution of that species. Given the current contribution of a species the mass flow rate of that species would be given by Eq. (4), where m is the mass of one molecule of the species and e is the fundamental charge. The total mass flow rate of the jet would be found by summation of the component mass flow rates.

Using this technique and actual time of flight curves[13] the average total mass flow rate for PIR emission ionic liquids becomes $1.2\text{x}10^{-12}$, g/s/emitter. An examination of the TOF curves shows that typically only the first two ion states are present in the emission in any discernable quantity. The averaged result is a 40% emission of pure ions and a 60% emission of the 1st solvated state. In reality the time of flight curve will vary from the ideal because of collisions of molecules and non-finite cessation of emission from the emitter. Based on the available data the potential associated with PIR emission for a typical ionic liquid is 1760 V.[13]

$$\dot{M}_i = \frac{I_i}{m * e} \tag{4}$$

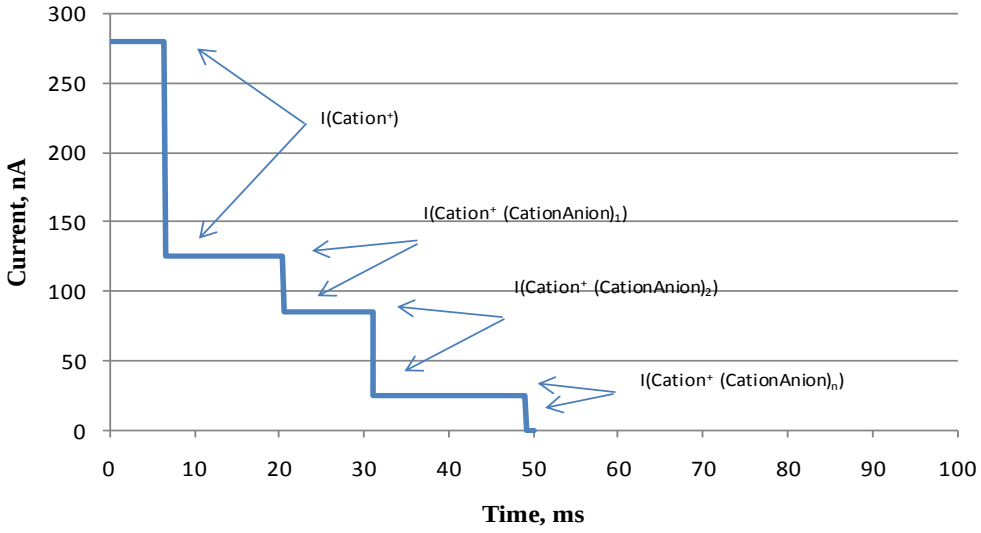

Figure 4. Example time of flight trace for nearly pure ionic emission

B. Results

Applying ideal equations for a charged mass in a potential field the specific impulse for the system would be 6526s for HAN and 4511s for 1-Butyl-3-methylimidazolium Dicyanamide. Using the power level and efficiency of the BHT-200 (200 W, 43.5%) results in a system thrust of 2.7 mN and 4.0 mN respectively for the propellants. Comparing these results with the performance of the BHT-200[28] (1390 s, 12.8 mN) shows a trade off in thrust for higher propellant efficiency when using an electrospray in PIR. If emitters of 50 μm inner diameter and 150 μm outer diameter were spaced 50 μm apart the system would consist of 34,798 needles and occupy a circular area with a diameter of 5.3 cm for HAN. A comparison of this arrangement with the space charge-limit shows that it would be operating at only 3-5% of the maximum.

IV. Dual-mode Benefits and Future Work

A. Dual-mode Benefits

A typical spacecraft thrust history is normally dictated years before it reaches the launch pad. Systems are often equipped only to perform station keeping and attitude control after separation, with a rare few having the ability to raise themselves to their final orbit. In a dynamically changing world and ever rising threat of on-orbit debris, the need for an operationally responsive space technology is increasing important. A dual-mode system will allow an on orbit asset to change orbit as the need arises rather than predicting the event. If a rapid orbit change is required the system can respond with a chemical high thrust burn and then gradually return to its primary orbit in a high efficiency electrospray mode. Also, in the event the asset is never called upon to perform such radical maneuvers, the system will be able to maintain its primary orbit for an extended period using the ionic liquid propellant purely in the electrospray mode.

B. Future Work

Using the performance predicted in this paper (shown in Table 3), a series of orbital maneuvers will be considered, including debris avoidance, orbit raising, and inclination adjustment. The goal is to determine and quantify any mass savings associated with an ionic liquid based dual-mode system. Accurately predicting the weight of individual system components such as power processing units and fuel tanks will be of utmost importance.

Table 3. Propulsion Systems for Dual-mode Benefits Study

Chemical Propulsion				
Propellant	Isp (s)	Thrust (N)*	mdot (kg/s)	Type
N2H4-NTO	270	10	3.7E-02	Bipropellant
N2H4-HAN	277	10	3.6E-02	Bipropellant
BIMDAC-NTO	239	10	4.2E-02	Bipropellant
BIMDAC-HAN	267	10	3.7E-02	Bipropellant
N2H4	227	10	4.4E-02	Monopropellant
HAN	218	10	4.6E-02	Monopropellant
Electric Propulsion (200 W)				
Propellant	Isp (s)	Thrust (mN)	mdot (g/s)	Type
Xenon	1390	12.8	9.4E-07	Hall
HAN	6526	2.7	4.2E-08	Electrospray
BIMDCA	4511	4.5	8.8E-08	Electrospray

*Chemical thrust assumed for a small spacecraft

V. Conclusion

The assessment of chemical propulsion performance for a series of ionic liquids has been determined through use of CEA. It was found that similar performance to traditional storable propellant combinations may be possible if ionic liquids are teamed with the HAN oxidizer. Performance of HAN and 1-Butyl-3-methylimidazolium Dicyanamide operating in the pure ionic regime of electrospray emission has been approximated and has been found to operate at much higher specific impulses when compared to a standard Hall thruster. Given these performance predictions and yet to be determined system weights a series of mission thrust profiles will be simulated to determine how much flexibility would be gained and what potential mass saving may be incurred by use of a dual-mode system.

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